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SLUDGE TREATMENT

AND

DISPOSAL

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SLUDGE TREATMENT AND DISPOSAL

By:

R. H. Andrews

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A. J. Harris
Director

Dr. J. A. Vance
Chairman

D. S. Caverly
General Manager

The Ontario Water Resources Commission

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INTRODUCTION

Improved techniques for treating sewage and industrial wastes have aggravated the serious sludge disposal problem. Much work has gone into the development of primary and secondary sewage treatment, so that up to 90% suspended solids and 75 - 90% Biochemical Oxygen Demand (BOD) may be removed from raw sludge, and an acceptable effluent produced. The treatment and disposal of the solids removed in sewage treatment is now realized to be equally deserving of attention.

This article reviews the various methods in use in Ontario and throughout the world for treating and disposing of sewage sludge as revealed in a literature survey. An attempt has been made to distinguish between techniques which merely reduce the water content of the sludge, and those which result in ultimate disposal. Sludge drying beds are discussed in detail because of their widespread use in North America, and the section on sludge lagooning draws on work performed by the OWRC, Division of Research.

I SLUDGE DEWATERING

Sludge is very moisture retentive, thus specific resistance and compressibility are important factors to be considered when studying the filterability, dewaterâbility, or drainage of sludge. Incompressible sludges can be successfully dewatered in continuous vacuum or pressure filters and in centrifuges; compressible sludge dewatering is much more difficult (3). Specific resistance is not a constant for any given sludge; it varies with pressure. (See below, Section VII).

Secondary, activated and humus sludges are more difficult to dewater than primary sludges. For desiccation, incineration and composting, fresh, i.e. undigested sludge, is often more suitable. However, the use of undigested sludge creates many other problems. Fresh sludge may contain harmful bacteria, and odours may be a serious drawback in any fresh sludge process. Volumes of sludge to be handled would be greater (5).

There are various methods of treating sludge to improve dewaterability. These include:

- Digestion (see Section II, below)
- Chemical conditioning
- "Porteus" method
- Freezing

The aim of any sludge processing is to reduce liquid sludge to its smallest possible volume before final disposal.

Chemical Conditioning

Sludge is conditioned by chemicals before filter pressing or vacuum filtering. The agents used are coagulants such as ferric salts, chlorinated copperas, aluminum sulphate and aluminum chlorohydrate. The rate of filtration increases up to a maximum point with increasing dosage, but then further doses of conditioner may even increase the specific resistance (21). The drainage qualities of frozen sludge improve when chemicals are added before freezing (10).

Elutriation and polyelectrolytes may be used to reduce the amount of coagulants required and themselves contribute to improved coagulation. Elutriation consists of a reduction of the alkalinity of the liquid sludge by diluting it and allowing sedimentation and decantation of the mixture. Soluble alkali substances which act as inhibitors of coagulation are removed in the process.

"Porteus" Method

The "Porteus" method is a heat treatment applied before filter pressing. Raw sludge is disintegrated before passing through a heat-exchanger, then it enters steam heated vessels where its temperature is held at 360°F for 30 minutes. The high temperature disinfects and conditions the sludge. After returning through the heat-exchanger the sludge is thickened before pressing (21).

Freezing

Freezing of sludge, particularly chemically conditioned sludge, much improves settling and draining qualities. The specific resistance may be reduced by a factor of 10^3. The drawbacks to artificial freezing are the expense of refrigeration and the necessity, at present, for batch operation. There is little reduction in specific resistance unless all of the sludge and its entrained moisture content is frozen completely before thawing (30).

Clements et al. (10) performed freezing experiments on small amounts of sludge. They found that:

- freezing was applicable to all types of sludge
- complete freezing was necessary
- settlement and filtration rates were greatly increased
- certain chemicals (see above) added before freezing improved these rates even more.

Freezing of sludge on drying beds is treated in Section VI.

II ANAEROBIC SLUDGE DIGESTION

Sludge digestion is itself a thickening process. As a sludge is digested its percentage moisture content is reduced and its volume changes (1).

$$V_1 = \frac{V[1 + P_1 (G - 1)]}{[1 + P (G - 1)]} \cdot \frac{(1 - P)}{(1 - P_1)} \quad \text{or} \quad V_1 \approx \frac{V(1 - P)}{(1 - P_1)}$$

V = old volume P = old % moisture G = specific gravity of solids in sludge
V_1 = new volume P_1 = new % moisture

Anaerobic sludge digestion (21, 52) reduces complex organic matter to a simpler non-objectionable state. Digestion renders sludge more amenable to dewatering, without nuisance, and renders sludge fit for easier disposal by lagooning and direct application to land. Digesters lower sludge volume, produce methane which can be used for heating, and conserve useful values that are destroyed by incineration. Organic matter is stabilized so that BOD is reduced. Long periods of retention at high temperatures reduce the number of pathogenic organisms. Disadvantages of digesters are the cost of equipment and the careful operation required.

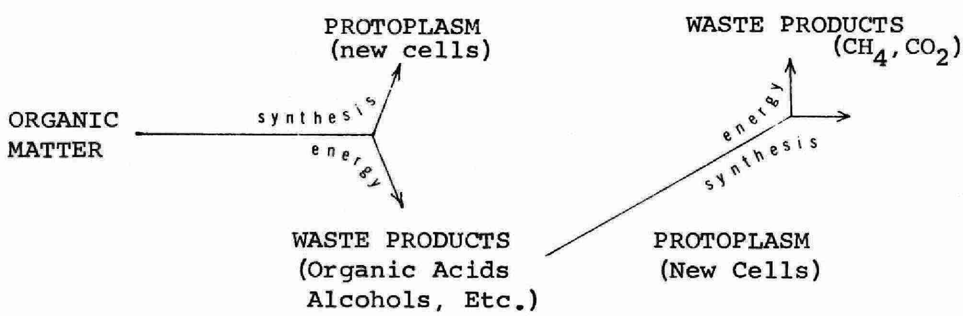

Figure 1 - Anaerobic Metabolism

Anaerobic metabolism includes stages of liquification (acid production) and gasification (methane production) (Figure 1). For the necessary mixed microbial populations there must be food of the proper composition and in the proper quantity at the proper time. Correct environmental conditions of temperature, pH, etc. must be maintained. Adequate buffering is particularly important since methane-producers require a pH between 6.4 and 7.2 for best operation. Alkalinity may have to be added to ensure an alkalinity greater than 2,000 ppm. Nutritional requirements of digester organisms are best met by frequent feeding with fresh sludge. Volatile acids concentrations between 200 and 500 ppm indicate satisfactory operation; much greater concentrations maintained over long periods may well lead to a breakdown of the process.

In two stage digestion, the first stage is heated to 85 - 95^{o}F and gas is collected. Effective mixing is essential. The digested sludge separates by sedimentation in the second stage, the supernatant with high BOD being returned to the plant for treatment. Mixing can be carried out by recirculation of the digester contents, mechanical stirrers, or gas recirculation. Grit and scum should not be allowed to accumulate.

Normally, suspended solids in domestic sewage averages 0.2 lb/capita/day. Primary settling removes 40 - 60% of the SS; the activated sludge process 85 - 95%. Concentration of sludge solids to be digested varies from dense primary sludge at 8 - 12% Total Solids (TS) to dilute activated sludge at 0.5% TS. Although volume reductions of 50% or more can be obtained by digesting mixed sludges (5, 48), in practice sludge concentrations of 3 - 5% solids are typical.

In some plants the specific resistance of the sludge has been somewhat lower than in others, caused possibly by pumping in the digesters breaking up sludge flocs (48). In these cases digestion prior to vacuum filtration would seem inadvisable.

Confusion between the terms "standard rate" and "high rate" digestion should be avoided (56). Standard rate digestion includes loading rates from about 0.04 to 0.10 lb Volatile Solids (VS)/day/ft^3 while high rate loading varies from about 0.15 to 0.40 lb VS/day/ft^3. There are other factors separating the standard rate concept from the high rate, the primary factor being the procedure used in handling the sludge solids. With the standard rate there is usually one digestion tank with an active zone and quiescent zone. Sedimentation and withdrawal of a relatively clear supernatant are part of the design. This means a longer detention period, but there is a large sludge storage capacity and operational upsets are less likely with the low loading rate.

The high rate loadings are based on operational experience. Only digestion itself takes place within the closed tanks, i.e. there is no solids separation or sludge concentration. As much volume as possible is available for the digestion process. The operational flexibility is limited, however, and careful control is required. The high rate process should find favour in the future as with increasingly severe operational standards and rising costs, installed plant capacity must be utilized to the best advantage.

III SLUDGE THICKENING

Sludge may be thickened at several stages in the treatment of sewage. Raw sludge can be thickened to 10 - 12% TS in sedimentation type concentrators, but activated sludge is difficult to thicken. Thickening prior to digestion produces a concentrated underflow and a clear supernatant, reducing the volume of sludge to be digested.

Thickening involves a reduction in sludge moisture content down to about 85%, and is normally achieved within sedimentation tanks or specially designed concentration tanks. There are a number of concentrators designed for use with raw primary, secondary or mixtures of sludges (56). The "picket fence" type is very successful, concentrating primary sludge to 12% TS and mixed activated and primary sludge to 6% TS. Another method based on incipient gasification and gas bouying of solids followed by decantation is used to concentrate raw sludge to 10% TS. Concentrators of a design similar to the flocculator-precipitators used in water treatment plants thicken activated sludge to 3% TS.

Torpey and Lang (50) proposed the elutriation of sludge which had undergone one stage of digestion as a method of concentrating sludge which was to be carried out to sea on barges. A digester liquor of 2 - 3% TS was elutriated to 4 - 7% TS, depending on the volatile content and loading rate. Storage of the elutriated sludge produced a marked decrease in the volume of sludge to be removed, with increases in the sludge solids content from 5% to over 10% after an 80-day retention period. They concluded that single-stage elutriation was as effective as a secondary digester with twelve times the volume.

Thickening can be obtained while sludge is being washed. In a two-stage digestion process, if sludge is washed with water after the first stage, flocculation in the second stage is quicker (5). The capital investment and high

operating costs make mechanical concentrators such as centrifuges, vacuum filters and vibrating screens unlikely for thickening of sludge before digestion, but depending on the method of final disposal, may be used for raw sludges.

To illustrate the use of some thickeners, at Grand Rapids, Michigan there are picket-type thickeners, primary sedimentation basins, and digested sludge storage tanks (55). The thickeners are circular tanks with rotating arms to stir sludge and scrape solids in the bottom. Tests were made to determine the effect of the depth of the sludge blanket on the percent solids in the withdrawn sludge. A maximum solids concentration of 7% was found at 70% of the total operating depth, but thickening equipment has a limiting mechanical stress, and solids concentrations of 5 - 6% could not be exceeded as the sludge scraper would not function. Pumps and piping must be such that withdrawn sludge can easily be sent to the digester or vacuum filters.

The primary sedimentation basins are equipped with sludge collectors. It is impractical to obtain concentrations of sludges of 8 - 10% TS without the use of special thickening tanks operated on a continuous flow basis. There are the limitations of operators in withdrawing sludge on a time or sight basis and the problem of pumping thick sludge. Thickening properties of sludge vary as a result of changes in treatment conditions and wastewater characteristics, making it necessary to vary the volumetric rate of withdrawal from the tanks. Changes in chemical composition definitely alter settleability characteristics.

Digested sludge concentration and storage tanks of two types were built: flat-bottomed equipped with stirring mechanisms and sloped-bottomed without stirrers. Sludge sent to these tanks followed accelerated digestion. The mechanism equipped tanks performed better, giving a sludge of 10% TS, with 1% TS in the supernatant, as against 8% TS and 0.4% TS respectively in the sloped tanks. Entrained gas was released by the stirring mechanism and sludge scraped into a central well.

To obtain the maximum benefits from sludge thickeners of any sort the transfer of the sludge to digesters or dewatering stages should be rigidly controlled. The most efficient operation of nearly all types of mechanical or physical dewatering techniques and the digestion process itself will occur if the sludge supplied to them is of a consistent type and uniform thickness. Conventional methods of controlling the pumping of sludge are becoming unsatisfactory as the volumes increase yearly. As more treatment plants become automated, the radioactive density gauge for measuring sludge density and controlling sludge flows has become more popular. The density gauge may be used to control flows from primary tanks or thickeners to digesters or directly to vacuum filters, or on activated sludge return lines.

IV SLUDGE LAGOONING

Sludge lagooning is used in Ontario as a method of thickening digested sludge so that a significant volume reduction takes place before further treatment (e.g. sand beds) or ultimate disposal (e.g. tank truck haulage to land). There have been lagoon studies at Lakeview, Peterborough and Stratford in Ontario, and at Winnipeg, Manitoba. Shallow lagoons may be used for sludge drying, although long retention periods are necessary.

There are many variables to be considered in designing and locating lagoons:

1. Possible nuisances - odours, appearance, mosquitos.
2. Size, shape and depth.
3. Loading factors - solids concentration of digested sludge, loading rates.
4. Lagoon bed material - underdrains, percolation.
5. Number of lagoons - retention time.
6. Sludge and supernatant removal - volumes, concentrations, methods.
7. Economics

Other factors affect lagoon operation:

Evaporation
Transpiration
Freezing
Weather - rainfall, temperature, humidity, solar radiation

1. Nuisances

In the past, nuisance conditions around lagoons have been due to several causes. Odours have been present on a few occasions when raw or only partially digested sludge has been discharged into the lagoon. Mosquito breeding has followed growth of vegetation in lagoons. Sometimes the area surrounding the lagoons becomes poor in appearance resulting in complaints

from nearby residents, and the proximity of residential areas to lagoon sites may influence the decision to install or not. At Lakeview odours were restricted to periods of sludge addition or removal and were not noticeable beyond 100 feet from the lagoons (49). These nuisances are not a major problem if care is taken.

2. Size, Shape and Depth

Lagoons of varying size, shape, capacity and depth have been tested. The volume of digested sludge to be discharged and the number of lagoons to be installed control the capacity to be sought. The shape should be designed for uniform sludge distribution and the width limited to twice the casting radius of the drag line used for excavation so that there is no need for heavy equipment to enter the lagoon to remove sludge.

Many attempts have been made to assess the effect of varying depths on sludge dewatering rates in lagoons. Jeffrey (23, 24), in an attempt to evaluate lagoons for drying rather than just dewatering, used sheet metal pipes as lagoons with pervious sand or soil beds. In using lagoons for drying underdrains or interconnected sand-filled trenches would be needed, but these would be costly and plugging of the bed would reduce the lagoons' effectiveness after a while. The drained liquors would have a high BOD and would have to be returned to the treatment plant. Jeffrey found that the discharge rate was erratic for the first three weeks but decreased at a uniform rate thereafter. He found that drainage rates were proportional to depth. For 2', 4' and 6' lagoon depths, 2.4' of sludge was added for each foot of lagoon depth. This was for a constant-head, sand-supported lagoon with no evaporation using sludge of 8% TS concentration. Soil-supported lagoons accommodated 90% as much sludge as the sand-supported ones.

Tests at Stratford and Lakeview indicated no great variation in dewatering rates with depth, although the underlying material was impermeable. A deep lagoon would be better

for area utilization. The maximum depth is limited by the size and shape of the cells, the sludge removal equipment to be used, construction costs and the level of the high water table. In practice, depths of 4 - 10 feet are feasible.

3. Loading

The solids content of digested sludge is generally rather low, about 2.5 - 5% TS. The filling of lagoons should be done as quickly as possible. Thon (49) suggests that in a two-cell operation, filling and decanting occupy the first half of the cycle followed by decanting only, so that the cell could accept additional sludge if emptying could not be carried out on time. In some areas, like Winnipeg, where freezing temperatures limit evaporation and sludge freezes, there may be a necessity for space for sludge storage so that large amounts of sludge may be discharged to the lagoons at greater intervals. While removal of frozen sludge is possible, the influent lines may freeze in winter, and these would have to be thawed for continuous operation. Care should be taken to ensure that the loaded sludge has been fully digested so that there is no odour problem and that there is uniform distribution of wet sludge in the lagoon.

4. Lagoon Beds

Jeffrey's tests with metal pipes were done with pervious sands and soils. When lagoons are used to effect only a volume reduction of the sludge it is desirable to build lagoons out of more clayey material to lower construction costs (i.e. to eliminate concrete cells, underdrains etc.) and prevent contamination of groundwater or surrounding land. Admittedly, percolation may form a significant percentage of the dewatering of the sludge, but unless the underlying material is very pervious, it will soon clog up and the problems mentioned above must be considered. The percolating liquid would be high in BOD content and could not be allowed to enter groundwater supplies. Underdrains greatly improve the sludge dewatering rate but do not seem to justify the expense.

5. Number and Retention Time

The number of cells required depends on the volume of sludge to be added, individual lagoon volume and the time needed to empty the lagoons. Fielding (17) and Thon (49) have suggested relationships between these variables based on experiences at Lakeview and Stratford. For continuous operation a minimum of two cells is desirable, while more will give greater latitude in operation. At Lakeview a 50% volume reduction could be obtained in about 25 days, plus the time required to fill the lagoon, which took 30 to 50 days, indicating the importance of minimizing filling time. Jeffrey (24) suggested using three lagoons in a three year cycle where each lagoon would be loaded for one year, left to dry for a year and a half and rested for six months. This use of lagoons for complete drying might have application in areas with a uniform, warm year-round climate, but would seem impractical in Canadian climates. Bubbis (6, 7) in Winnipeg found that four foot lagoons required two years or more to dry, or 18 months with underdrains. However, there was no drying in winter and no percolation because of the impervious nature of the beds.

6. Sludge and Supernatant Removal

Many investigators have stressed the importance of supernatant withdrawal in dewatering sludge in lagoons. Decanted liquors are returned to the sewage treatment plant and should have as low a solids content as possible. Removal of the supernatant can be achieved by decanting weirs, pumping, or any method that maintains a low velocity at the sludge-supernatant interface. In Winnipeg adjustable overflow weirs were used. At Lakeview syphoning was achieved by using one-inch diameter, flexible, plastic pipes fastened inside wooden frames just below the sludge surface. Since the supernatant pond level was below lagoon level, the syphon was started by operating a diaphragm pump and flow of the supernatant continued until the suction end of the pump reached heavy sludge. Supernatant was withdraw as soon as it was available. At Stratford some 50% of the liquid removed was by decanting.

Solids concentrations of 8 - 12% can be obtained, corresponding roughly to volume reductions of 40 - 65%, depending on the concentration of the applied digested sludge. There is an increase in percent solids with depth in the lagoons. Above a solids concentration of 7 - 8% pumping can be difficult, so if sludge is to be removed from a lagoon by pumping it will have to operate below maximum efficiency. A portable gasoline-driven pump was used at Lakeview and was limited to 8% TS. It is difficult to avoid drawing thinner supernatant into the pump. Gravity withdrawal at Peterborough resulted in selective removal and there were pipe-clogging problems. Thon (49) suggests the use of conveyors which would pick up sludge and deliver it to trucks at ground level.

In Winnipeg, thickened sludge is removed in winter when it is frozen by rippers and scrapers, but this would not be a useful removal technique in southern Ontario with its milder winters. A front-end loader could be used if the lagoon bottom was paved. In summer 12-yard scrapers are used in Winnipeg, but since this equipment is expensive, it is most effectively used after a dry period.

7. Economics

The use of sludge lagoons to thicken sludge before tank truck haulage to land will decrease haulage costs by greatly reducing the volume of sludge to be transported. A volume reduction of 50% can be obtained with suitable lagoon design and operation. If drying beds are to be used to dry the sludge after detention in lagoons, the increased solids concentrations should increase drying efficiency. These approaches to sludge dewatering are generally cheaper than mechanical methods which do not lead to ultimate sludge disposal. At Winnipeg the cost of lagoon-drying sludge, excluding maintenance, was $0.80 - 1.00 per ton of dry solids. For sludge removal in summer using a scraper the cost was $0.78 per ton of solids and in winter $1.06. At Peterborough, with a tank truck haulage rate of $0.50 per cubic yard and a sludge volume reduction of 50%, the saving to the city would be about $15,000 annually in haulage costs,

which is about equal to the expected lagoon facilities construction costs. A sludge lagoon entails a considerable capital investment. McTavish (32) indicates the costs of small lagoons at $4,000 - 5,000 per acre, not including haulage or maintenance costs. In Winnipeg the dried sludge is placed on concrete pads where the public removes it.

There are several other factors which influence lagoon operation. These include rainfall, temperature, evaporation, transpiration, solar radiation and freezing of the sludge.

Evaporation

Although considerable work has been done on dewatering rates of drying beds, relatively little has been done on lagoons, with their greater depths and frequent loadings. Jeffrey (24) found that evaporation from model lagoons was 44% of the free surface evaporation. He also found that drainage alone results in a sludge mass of uniform moisture content, whereas when evaporation takes place as well, the effects are restricted to a six-inch layer near the surface, below which the moisture content increases rapidly with depth. In some climates evaporation would play an important role, but in Canada rainfall equals or exceeds evaporation in many areas so its benefit is lost. When sludge freezes there is little evaporation as an insulating layer ¼ - ½" thick of dry, powdered sludge forms on the surface (6).

Transpiration

Jeffrey investigated the importance of transpiration from lagoons containing tomato plants. The sludge must be dry enough to support plant growth; smaller depths of sludge support growth. His studies showed that transpiration accounted for moisture removal up to 50% of that removed by evaporation. Transpiration would account for little moisture removal in lagoons used only for thickening sludge, where depths are greater and the sludge does not become too dry. Plant growth would also tend to attract mosquitos.

Freezing

In cold climates where the sludge freezes in winter it is possible to remove it by scrapers. The sludge is put on pads to dry, where in the spring it thaws readily. For deeper lagoons in milder climates the main problem is to keep the influent lines open during the winter. Either frost protection should be provided or the line should be thawed to be kept open.

Weather

Although rainfall adds to the volume of sludge to be dewatered, McTavish (32) found that heavy rains elutriated the sludge and increased the solids concentration. Temperature is of the utmost importance in dewatering, and solar radiation has been mentioned as being more significant than wind speed or humidity in the drying of sludge by evaporation (47).

V TANK TRUCK HAULAGE

Tank truck haulage of digested sludge to be applied directly onto farmland, golf courses etc. is common (25, 26, 51, 53). This is the only true form of sludge disposal; it is also the cheapest. Sludge has to be carried in watertight containers if the moisture content is greater than 75%. Generally the solids content is only a few percent, as the sludge goes directly from the digester to the truck, but if the sludge is thickened a solids concentration of 8 - 12% may be achieved, with consequent volume reduction.

Cheap land must be available for dumping near the sewage treatment plant, i.e. a round trip of 20 miles may be economic if roads are good. The Maple Lodge works, in England, has found their haulage distance increasing yearly (26). The farmers there have been pleased with the beneficial effects of sludge on their crops and the method of distribution. It is imperative to avoid nuisance complaints. It is hard to achieve greater expansion without increasing costs, yet even though it may be feasible to spend more on haulage, the major problem is to maintain adequate supervision over the land distribution. Most sludge products are soil conditioners rather than fertilizers; potash and/or lime or other constituents may have to be added if fertilizer requirements are to be fully met. By contracting out the sludge disposal money may be saved, but then it is difficult to maintain control over the operation. If raw sludge is to be hauled great care must be taken to avoid odour nuisance.

The design of the tank truck is important. The design and capacity of the tank, design and control of the spreader valves and plates, chassis design to meet heavy-duty conditions, and speedy filling are factors which should be considered. Larger plants require tandem and four-wheel drive vehicles. Tanks should be round or oval to minimize structural cracks. The use of a top-operated valve, with the valve located in the tank itself, for the sludge discharge line, will prevent freeze-up during winter operation. The tank must be constructed with adequate internal baffles, inspection and

loading manholes and vacuum relief valves on top. Tank capacities might range from 600 to 2,400 gallons, the length of haul and plant capacity governing the capacity.

Costs of tank truck haulage in Ontario are about \$1.00 - 1.50 per cubic yard at present. A few years ago costs of \$0.50 a yard were common and may still prevail in rural areas where haulage distances are small. This is for digested sludge with a solids content of a few percent (2.5 - 5%). Overall costs may be substantially reduced by thickening the sludge before haulage.

At Maple Lodge works in 1961, where the trucks are owned by the plant, the total cost of complete disposal of liquid digested sludge, including capital charges, was £6 (=\$18.00) per ton of solids. At Croyden, England the costs were only £1 (=\$3.00) per ton, the difference in cost probably being due to the location of the land disposal area. More recent estimates put this figure at £10 (=\$30.00) a ton, but this is still the cheapest disposal method in England.

With the distance of hauls increasing in some areas, the possibility of pumping the sludge to stand pipes has been suggested to that the trucks might be used for distribution only. When fields are muddy and perhaps impassable the sludge might be put into a small reservoir pit and distributed by some rain-gun system. These problems are probably more pressing in England than in Ontario. The comparative haulage rates indicate this, although capital costs are included in the English estimates.

In disposing of sludge on land care must be taken to avoid agricultural pollution, especially in grazing areas, and the productivity of the soil should be watched.

VI SLUDGE DRYING BEDS

Drying sludge to the point where it can be handled as a solid is commonly achieved by the use of drying beds (1, 44). High labour costs are a limiting factor in their continued use, particularly in England, but they are still practical for relatively small installations. For large plants of 25 mgd capacity or more, costs are probably lower when sludge is vacuum filtered and incinerated. Sand beds are best suited to well-digested sludge so that odour and fly nuisance can be avoided and for other reasons detailed below. Apart from labour and plant capacity considerations, there are other factors which determine whether drying beds should be installed. These include the availability of cheap land, proximity to housing where odours might be a nuisance, industrial wastes which might be detrimental to bed performance, the climate and, of course, overall costs compared to other drying or disposal methods.

In Ontario about 20 - 25% of the plants in operation use uncovered drying beds. Their greatest application has been in plants serving populations up to 25,000 (8, 44). In the U.S.A. some two-thirds of the sewage treatment plants employ drying beds (36).

The construction of drying beds is fairly expensive and much of the attention in construction goes to the filter medium and underdrains, although other facets of the building can be important. The beds are generally enclosed in watertight concrete or brick basins to avoid possible groundwater contamination. In some areas this can be a critical problem (26). The walls of the bed may extend 15 - 18" above the bed surface. The beds themselves consist of graduated layers of sand or fly ash with coarser grains of gravel or clinker underneath, in which are laid underdrains. The thickness of the two layers might typically be 18 - 24". The filtrate should be returned to the treatment plant as its BOD content will be high.

The area of the beds depends on the volume of wet sludge expected. The per capita loading requirements in England are suggested as being 1.5 - 2.5 yd^2 per capita, but with better climates, or for summer drying only, a higher figure would be permissable (26).

Even distribution of wet sludge in the beds is important so the method of discharge into the beds from the digester should be carefully considered (44). Gravity discharge is the most economical. Savings in piping can be made by placing the beds close to the pumping unit or digester. Underdrainage systems should be placed above flood levels of receiving waters adjacent to the plant. Sluice valves should be added for supernatant discharge, if needed.

After several fillings of the beds there may be some clogging or sealing of the drainage medium, but occasional flooding of the beds with clean water may prevent this. Large amounts of grit also affect bed performance. When removing the dried sludge care must be taken not to remove sand from the filter, although periodic renovation of the filter is required in any event. The use of hessian to protect the beds has been suggested (26); it has worked well in South Africa. Hessian improved bed drainability and required no maintenance.

Increasing interest has been shown in mechanization of the dried sludge removal process, especially in England where the labour problem is acute (26, 27). In small plants manual labour may be used while in larger plants concrete runways may be provided for removal by trucks. Mechanized forms of sludge removal are expensive but at Maple Lodge works in England the mechanical sludge lifting equipment has been efficient. Dried sludge can be put on concrete pads to dry further and possibly be picked up by local farmers and gardeners for soil conditioning, but in some areas and seasons the plant will have to dispose of the dried sludge. It was found at Maple Lodge that the sludge had to be drier for mechanical lifting then manual lifting. The method of sludge removal is an important factor in governing the operation of the beds, as the extent to which the sludge is dried to a

"liftable state" or beyond affects the operational costs (47). The moisture content of the sludge on removal can vary from 40% TS upwards. A small charge is sometimes made for the dried sludge if there is sufficient demand.

At Maple Lodge the wettest sludge lifted had a 70% moisture content. In summer some sludges had as little as 30% moisture. Usually the sludge was assumed to have 50% moisture, and was applied to farmland by trailers with rear-mounted flails.

The two principal mechanisms of dewatering on drying beds are drainage and evaporation. Drainage usually accounts for the main part of sludge dewatering on drying beds. The more readily a sludge drains, the higher the proportion of water removed by drainage. Swanwick and Baskerville (47) found that drainage could account for anywhere from 22 to 85% of the water removed. The relative proportions of drainage and evaporation are influenced by the solids content of the wet sludge. They considered two stages of dewatering, a "liftable state" corresponding to about 40% TS, and a further stage of drying. The liftable state represents the minimum degree of dewatering required before sludge can be handled as a solid rather than a liquid; subsequent drying is by evaporation. The solids content at which various sludges reach the liftable state varies considerably. Sludges which drain well dewater more uniformly and become liftable at lower solids contents. It is most economical to remove sludge from the beds at the lifting stage and dry the sludge by another method or dispose of it.

Several workers have attempted to assess the effect of evaporation from sludge drying beds by comparing it with the evaporation rate from a free water surface, but as Nebiker (33) points out, their conclusions differ widely because of differences in experimental technique and definition of sludge drying rate. In order to estimate the amount of drying due to evaporation alone, Coackley and Allos (12) suggest that there are two distinct groups of factors influencing air drying of sludge. These are external factors like temperature, relative humidity, and wind speed, and internally, chemical and physical characteristics of the sludge.

They found two distinct drying periods, a constant rate period when there is a high moisture content and a falling rate period. Nebiker's studies showed that the evaporation rates from most sludges were identical and that this rate was similar to that from a free water surface.

Quon and Tamblyn (36) found that when evaporation was the only dewatering mechanism, the rates of water evaporation from a free-water surface and a sludge surface as a function of the radiation intensity incident on the sludge surface were essentially equal. They also found an interaction between drainage and evaporation, the effect of drainage being to prevent the formation of a free-water surface on the sludge and reduce the evaporation rate. Their studies have a direct application as a few plants in the USA have constructed paved drying beds with limited drainage systems. On these modified beds sludge takes about the same time to dry, but a more economical operation is achieved since the sludge can be removed mechanically and with a higher moisture content than on normal beds.

Decanting of the supernatant is not an important part of the dewatering, as it is in sludge lagoons. Kershaw and Wood (26) found that they drew off supernatant only after heavy rains or when the sludge was frozen since the mechanical lifting equipment does not lift frozen sludge easily.

A recent development is the use of a wedge-wire medium to replace the sand or ash filter (21, 29, 39, 41, 42). The principle of the wedge-wire filter is to use support water to enable the sludge to settle on the medium and form its own filter layer, then remove the support water so that drainage may take place without a breakthrough of the sludge solids. In tests to date it has shown to be particularly effective for secondary sludges and for vegetable wastes. The wedge-wire beds are more expensive to construct than conventional sand filters, but maintenance costs are low, turnover is more rapid, and they lend themselves to mechanical sludge removal techniques.

The effectiveness of drainage and evaporation in drying the sludge and the **relative importance** of each is determined by many factors:

1. Source and Type of Sludge
2. Solids Content of Wet Sludge
3. Industrial Wastes in Sludge
4. Sludge Transfer to Beds
5. Climate
6. Sludge Depth
7. Coagulants and Elutriation
8. Freezing and Thawing
9. Coverings

1. Source and Type of Sludge

The source and type of sludge influences its dewaterability. Swanwick et al. (48) who found that digested sludges showed a marked variation in specific resistance from plant to plant thought that this might be due in large part to excessive agitation in the digesters caused by pumping during which the sludge flocs may have been broken up. Mention has already been made of the use of specific resistance as a quantative measure of filterability. This applies also to drainability. The drainage time of a particular sludge is proportional to the specific resistance. Since decantation and evaporation may occur from drying beds, the significance of the specific resistance depends on the relative importance of drainage. It was found that sludges, which filterability measurements showed should drain faster, gave a much better bed capacity.

Sludges should be well-digested before drying on beds to avoid fly and odour nuisance (21, 44, 47). In any event, well-digested sludges tend to dewater better, as dissolved gasses in the sludge are released, tending to float sludge particles and facilitate drainage. It has been noted that the drying quality of "dead" sludges which have been aged for 5 - 6 months is very poor.

2. Solids Content of Wet Sludge

Hazeltine (20) stressed the importance of defining a "gross bed loading" to describe bed performance. This loading is the number of pounds of solids applied per square foot per 30 days of actual bed use. He also defined a "wet bed loading" as being equal to the gross bed loading times the percent solids in the sludge removed. Wide variations in the solids content of the sludge removed affect the cost of cleaning the beds and the amount of sand replacement required. Hazeltine stated that next to temperature, the solids content of the applied sludge was the most important factor in bed performance, and after that, the solids content of the sludge removed. Hence he defined the above terms to eliminate the percent solids in the sludge and permit the study of other variables. It is possible that the solids loading is more important than the hydraulic loading (47). Swanwick feels that the optimum may be 20 lb/yd^2 whereas at Maple Lodge investigators found little relation between drying time and applied solids, which ranged from 10 to 21.5 lb/yd^2 (26). The drying time ranged from 30 days in summer to about 170 days in winter. The digested sludge varied from 3.6 to 5% TS and it was felt that a solids loading of 20 - 25 lb/yd^2 was the maximum which could be achieved. The capacity of the beds was 1.5 persons per square yard. The solids loading of the bed should be near the limit of volumetric loading as the less water there is to dry, the quicker the sludge will dry. It is desirable, therefore, to thicken the sludge before applying to the beds.

3. Industrial Wastes in Sludge

The presence of industrial wastes which will alter the characteristics of the sludge to be handled may discourage the use of drying beds. Generally, wastes which interfere with digestion will affect the dewatering operation and might exhibit the following characteristics (44):

- -high total of volatile or non-volatile solids
- -floating material
- -greasy or high fatty content wastes
- -high volume wastes
- -extremeties and fluctuations in pH

Industrial wastes including high suspended solids, wastes, phenolic, acid or alkaline wastes, or toxic metals would account for these problems.

4. Sludge Transfer to Beds

Sludge can be applied to beds by gravity flow, pumping etc. It is important that the sludge be distributed evenly over the beds (20, 44). Splash pads at the pipe inlet will assist in even distribution of flow and prevent scouring of the sand. Arrangements should be made for draining and flushing the lines following use. Beds with uneven distributions of sludge or concentrations of solids will not dewater well.

5. Climate

The climate naturally plays a great role in drying sludge on beds, so that in good weather a sludge will dry to 60 - 70% moisture in two weeks. Temperature is the governing factor. Many areas can use beds successfully in summer but find them of no use in winter. Hazeltine (20) found that bed loadings were higher in summer than in winter in Pennsylvania. In winter there is often little or no evaporation, there is less solar radiation, often more cloudiness and precipitation, and sometimes the beds freeze completely. A small amount of rain may not affect the bed performance (eg. at Maple Lodge (26)). Glass-enclosed beds may limit the effects of bad weather but are more costly. In areas where winter operation of drying beds is impractical, provision should be made for storage of the sludge and proper digester operation.

6. Sludge Depth

Many investigators have tried to determine the optimum depth of applied sludge to be dried. Unlike sludge lagoons, where sludge may be added continuously and decanting of supernatant is important, sludge must be applied to beds at one period, and all the dried sludge removed before further addition is made. Swanwick (48) found that the drainability

of the sludge influenced the depth to be used, in that lower depths improved the bed capacity for slow-draining sludges. Depths of 8 - 12" are commonly used, although lesser and greater depths have been tried. Swanwick (47) suggested that depths of 9 - 10" are best in his experience and found that the drying time increased at the depth squared. Hazeltine (20) found that 9" was the optimum depth under glass-covered beds. The depth may be limited by the design of the beds, the solids content of the applied sludge, or the maximum thickness of the sludge cake that can be lifted by mechanized removers. At Maple Lodge the standing depth of sludge is limited to 10", and 2½" is the maximum thickness of sludge cake which can be lifted. Quon and Johnson (37) suggest that as more information is gained on the various dewatering mechanisms, thin sludge applications of 3 - 4" may be used.

7. Coagulants and Elutriation

As coagulants improve the dewaterability of sludge to be vacuum filtered or pressed, so they improve drying bed performance. Lime may be added to keep down odours and insects as well as to maintain sludge porosity. Suggested feed rates of alum might be 1 lb of alum for 100 to 300 gal of sludge (44, 51). Swanwick noted an increase in coagulant demand after digestion (48), also that elutriation improved filterability considerably and that for a slow-draining sludge, elutriation improved bed capacity. Hazeltine found that coagulant was helpful in the autumn months, but not much use at other times of the year.

8. Freezing and Thawing

It has been shown both on a laboratory scale and in practice that when a sludge is frozen fully and then thawed it releases its moisture much more readily than normal (1, 2, 10). In Winnipeg the frozen sludge is removed from the beds and put on concrete pads where it rapidly dewaters in spring (6, 7). Unless the sludge can be removed from the beds in a frozen state and left to thaw elsewhere, freezing is not much help in dewatering as the beds are not used during the winter. The characteristics of the sludge which has frozen and thawed

are different from ordinary dired sludge. It is finer-grained and does not have any large cracks, and is easily pulverized to resemble a light, dry soil. This might not be an advantage when removing the sludge from the beds manually, however. It is believed that the effect of freezing is to overcome the attraction of the colloidal particles for water, and this permits the water to drain rapidly.

9. Coverings

The use of covers over drying beds has been attempted in order to minimize the effects of bad weather although usually the costs do not justify their installation. Other drying methods become more reasonable if the weather is unsuitable for beds. Coverings are useful in winter in a country like England. Glass covers are better than opaque as solar radiation can aid evaporation. Former increases in bed performance of 100% have been experienced, but in some cases the performance has decreased. Where rainfall is high, they may be justified.

VII MECHANICAL DEWATERING METHODS

Mechanical dewatering methods are becoming increasingly popular and economically feasible as communities run out of space for sludge lagooning or sand beds, and land for liquid sludge disposal becomes too expensive or too distant from the treatment plants. Especially in large cities, the question is not whether mechanical methods should be employed, but which method would best serve the community. The main types of equipment used will be described under the following headings:

1. Vacuum Filters
2. Centrifuges
3. Presses
4. Rotoplug Sludge Concentrator
5. Other Methods

1. Vacuum Filters

Vacuum filters are commonly used to dewater sewage sludges in large treatment plants, and are probably the most widely used of the mechanical methods. Many types of filters have been proposed, and over the years there have been significant advances and research in such areas as filtration theory, filter media, conditioning and elutriation, and in the design of the filters themselves.

The characteristics of the sludge to be dewatered have a large bearing on the efficiency of filtration. These include (31):

- size, shape, compressibility, and charge of the solids
- viscosity of the filtrate and sludge
- chemical composition
- solids concentration, dissolved and suspended

Despite these varying characteristics, operational experience has produced sufficient data to establish criteria for the design of vacuum filter installations for the various types of sludges encountered. The vacuum filtration of fresh sludge used to be a problem because colloidal materials and greases clogged the filter media. The coil spring vacuum filter now in use is non-clogging. It has been found generally that when a non-clog filter medium is used, fresh sludges dewater better than digested activated sludges (11, 31, 54).

The concepts of specific resistance and compressibility were introduced in Section I. The specific resistance may be defined as the resistance of a unit weight of filter cake per unit area at a given pressure (31). The specific resistance may be used to study the effect of the solids content and chemical conditioning on sludge filterability. Theories of filtration were developed by Ruth and Carmen; the following relationship is due to Carmen (3):

$$\frac{dV}{d\Theta} = \frac{PA^2}{\mu\ (rcV + R_mA)}$$

where c = solids concentration, P = force
A = filter area
r = specific resistance of sludge
μ = viscosity of liquid phase
V = volume of filtrate obtained at time Θ
R_m = resistance of filter medium

The specific resistance is not a constant for any given sludge; it varies with pressure:

$$r = r'P^s$$

where s = coefficient of compressibility

This illustrates the significance of the compressibility of the sludge. The rate of filtration is proportional to the filtering force only if the sludge is relatively incompressible. Swanwick et al. (46, 48) have carried out extensive studies on the specific resistance of various sludges.

The most common types of filters are variations of the rotary drum vacuum filter employing some kind of fabric as a filter medium. Fabrics used have included cotton, wool, felt, dacron, saran and polyethylene (31). The synthetic

fibres are claimed to have a longer life, a greater yield in many cases, and are easier to clean. The ideal filter medium offers no resistance to the flow of the liquid through it. As mentioned above, clogging and blinding of the medium is a major problem, and the coil spring filter has alleviated this and other unsatisfactory aspects of the fabric-covered vacuum filters in the dewatering of fresh sludge (11).

The drum vacuum filter consists of a hollow cylinder covered with filtering cloth or layers of steel coil springs. The filtering medium forms one side of a series of hollow cells in which various pressures can be produced. The drum rotates slowly about its axis and the lower portion passes through a tank containing this sludge. A vacuum picks up a layer of sludge as the filter surface passes through the trough and as the drum rotates a cake is formed on the outside of the filter medium. Dewatering occurs until the filter cake is discharged from the drum and conveyed away for incineration or disposal. The filter medium must be washed at some stage of the process and the sludge tank is generally fitted with some sort of agitator to keep the solids in suspension and maintain a regular sludge consistency. In designing a vacuum filter a proper balance must be maintained between the degree of submergence of the drum, the speed of rotation of the drum, the vacuum and the filter medium (1).

The amounts and types of conditioning agents, filter aids, and elutriation of the sludge to be dewatered play an important role in effective vacuum filtration. The types of conditioning agents used have been mentioned in Section I; often a combination of lime and ferric chloride is used. It is essential that coagulants be added in the right total amounts and in the right proportions if maximum efficiency and minimum cost is to be attained. It has been found that digested sludges require more conditioning chemicals than fresh sludges due to the gain in bicarbonate alkalinity during anaerobic digestion. Since conditioner costs are high, they are an important consideration in determining the feasibility of vacuum filtration at a plant.

In recent years natural and synthetic polyelectrolytes have been used in conjunction with the common coagulants to improve yields. In some cases the polyelectrolytes reduce the amounts of chemicals required and in others serve themselves as the coagulant. Although expensive, their use has been proven effective by high yields in many applications. Certain polyelectrolytes may be quite effective in one situation and of little use in another, however, so experimentation continues in many plants.

Elutriation is another necessary process which helps reduce coagulant demand. The main plant in Toronto in extending their filtration facilties gave much thought to elutriation of the sludge prior to conditioning, and built new, 17' deep tanks in which the sludge was to be thickened and its alkalinity reduced with a minimum loss of solids in the overflow (13).

Filter aids and precoating have been used for many years (14). Filter aids build up a porous, permeable, and rigid lattice structure on the filter medium which retains the solid particles and allows the liquid to pass through. The most important filter aids are the diatomaceous earths which may be used to precoat the filter medium or mixed with the liquid to be filtered. Whether the object of the precoat is to prevent clogging of the filter medium or to hold back fines from passing through, its function is to become the filter medium itself.

The filtration of fresh sludge rather than digested sludge appears to have more arguments in favour than against (11, 31, 54). It is claimed that the use of undigested sludge results in odours and makes final disposal more difficult. The former problem can be avoided by adding lime to the sludge and if the filter cake is incinerated or safely buried in a disposal pit the latter problem is solved also. Digested sludge is more difficult to dewater than raw sludge, probably because the fibrous nature of the raw sludge is often destroyed in the digestion process. The coagulant demand increases after digestion, resulting in high operating costs. If the digesters can be dispensed with entirely in the design of a plant, a considerable capital saving is effected. Filtration rates, which are normally in the range of 1 - 10 lb of dry

solids/ft^2/hr for sewage sludge, are higher when raw sludge is filtered. The moisture content of the filter cake is commonly 75 - 80%.

Vacuum filtration is widespread and its proponents can point to many advantages over other dewatering methods, particularly digestion followed by drying on sand beds (11, 13, 31, 54). The plant area required is small, and capital costs are lower when filters are installed instead of digesters and drying beds. Vacuum filters allow greater flexibility in operation, can be coordinated with the remainder of the plant, can be run on a routine schedule, and are unaffected by the weather. Little labour is required, and manual handling of the sludge is eliminated. Since there are no biological reactions involved, operation is not affected by temperature changes or shock loads. Operating costs depend largely on whether raw or digested sludge is being filtered, the raw sludge requiring less conditioning, but in general are considerably higher than costs of the treatment and disposal methods outlined in the previous pages. One of the main drawbacks to vacuum filtration is that further drying or incineration is required before final disposal, adding to the costs. In some cases the moist sludge cake may be applied directly to land, but if not fully digested, great care must be taken to avoid contamination of groundwater supplies or odour problems.

Since the amount of conditioner depends on the volume of sludge to be filtered, any concentration of the sludge will reduce costs. The moisture content of the wet sludge is a critical factor in cake production and the economics of this dewatering method are directly related to the sludge moisture content (11). Operating costs including the cost of conditioners are about \$10 - \$20 per ton of dry solids produced.

2. Centrifuges

The chief use of centrifuges has been in the USA where investigators have reported varying degrees of success in dewatering sewage sludge (16, 38, 57). The solid bowl

centrifuge consists of two rotating elements, a solid bowl, and inside it a screw conveyer. The bowl is driven by a motor and the conveyer through a gear system that revolves the conveyer at a slightly lower speed than the bowl. Sludge is fed through a feed-pipe inside the conveyer to a pool of sludge inside the bowl. The solids settle against the wall and are picked up by the screw conveyer which moves them to the discharge point while the clarified liquid leaves by effluent ports in the bowl. Variables such as bowl speed, sludge pool volume and conveyer speed must be coordinated. Process variables include the solids feed rate, solids characteristics, coagulants and temperature of the sludge.

White and Burns (57) reported a 70 - 75% recovery of solids and a cake with moisture content ranging from 67 to 72% using digested sludge. Raw sludges gave lower cake moisture contents, but activated sludges dewatered to only 82 - 88% moisture. They claim moderate initial and operating costs, a minimum of operating attention, and they require no chemicals. Operation is simple and year-round, and both thick and thin sludges can be handled at operating costs of $6 - 12 per ton of dry solids less than those of vacuum filtration plants.

Radcliffe (38) used a solid bowl centrifuge for concentrating waste activated sludge and dewatering digested sludge. For digested sludge with 4 - 6% TS a cake of 74 - 86% moisture was produced but improved performance was noted when coagulants were used. Costs were estimated at $8 - 12 per ton of dry solids for a feed rate of 500 - 1,000 lb/hr. Activated sludges of less than 0.5% TS were concentrated to 5 - 7% TS, increasing the digester capacity by 30 - 50%. Radcliffe claimed neglible maintenance costs and no labour costs (the centrifuge was run for only 3 - 5 hours every other day). Power consumption added about $25 a month to the costs.

Ettelt and Kennedy (16) experimented with a disc (or nozzle) centrifuge as well as with solid bowl types. They found the disc centrifuge unsatisfactory because the sludge discharge nozzles clogged repeatedly. The solid bowl centrifuge gave a decrease in solids recovery with higher loadings, although the addition of a cationic electrolyte improved the solids production. By lowering the liquid level

in the centrifuge a greater solids concentration was obtained, but again at the cost of lower recovery. The poor solids recovery is one of the main drawbacks to this method, capacities per unit are relatively low, and for extensive use power requirements and operating costs are high.

3. Presses

Filter presses are used primarily in chemical process industries. High capital costs and the costs of labour, filter media, and conditioning agents have prevented their use in dewatering sewage sludge in North America, but they have enjoyed some measure of success in Great Britain and on the continent (14). For most industrial sludges mechanical pressing is more economic than some form of heat treatment.

Filter pressing is achieved by using massive units in a batch or semi-batch operation (21, 30). Presses consist of a series of recessed plates covered with a replaceable woven fabric. Under pressures up to 100 p.s.i. the water passes through the fabric and the sludge solids are retained. The cake is removed as a slab with a moisture content of 55 - 75% , although industrial sludges may be drier. The filtrate is returned for treatment and as with vacuum filtration, conditioning agents must be used. Isaac (21) gives a cost of about $15 per ton of dry solids for pressing a mixture of primary and secondary sludge using lime as a conditioner. The main advantage of filter pressing is the dryness of the cake produced, and if the cake is stacked and dried further it may readily be used to produce a soil conditioner or fertilizer base.

Mechanical presses are of two types, screw and revolving-disc (15). In the screw press, sludge is fed through a horizontal cylinder where a revolving screw mechanism exerts an intense pressure on the sludge, forcing the release of its moisture through small openings along the periphery of the cylinder. The revolving-disc press allows sludge to enter the top and fall between two, large, revolving discs, the sides of which come together when rotating, forming a cone. The pressure extracts the water which is removed at the bottom and the pressed material is discharged at the back opposite the intake. Mechanical presses are economic for pulp and paper sludges and some other industrial sludges.

4. Rotoplug Sludge Concentrator

The rotoplug concentrator is in use in the USA and has been introduced to England (3, 4, 45). This is a continuous, two-stage process, the first being a thickening procedure and the second compression filtration. In the thickening cells the water is removed from the sludge by drainage through a fine nylon mesh. The rotation of the cells causes the sludge to form into a plug which dewaters further by the action of its own weight. The end of the plug is cut off and dropped into the compression filter where two, heavy press-rolls acting in conjunction with a stainless steel, wedge-wire drainage wheel cause final dewatering. The first stage thickens the sludge to 10 - 15% dry solids and the second gives a final sludge cake of 20 - 30% DS. The sludge volume is thus reduced to about one-seventh of the original feed. No chemical conditioners are required. Being a self-contained unit, the only auxiliary equipment needed is that required to feed in the raw sludge and remove the products of filtration, and some method of washing the filter surfaces periodically (40).

Sludge fed to the concentrator should be of uniform consistency. Raw sludge has been successfully dewatered, but Suriyadasa (43) reported that digested sludge failed to form a plug, possibly because it contained insufficient fibrous matter. For experimental purposes he added newsprint to digested sludge and was able to form plugs. In small plants fresh sludge should be used in any event to avoid the cost of digestion, but mixed raw and activated sludge can be dewatered.

One of the main drawbacks to the rotoplug concentrator is the high BOD and amounts of suspended matter in the filtrate. If the filtrate is returned to the sewage plant without pretreatment serious overloading may occur. To overcome this problem, the filtrate should be settled for several hours, thereby reducing the BOD and suspended solids considerably. The denser portion of the filtrate may be recirculated through the concentrator. The filtrate has also been successfully dewatered on drying beds. The dewatered sludge represents a disposal problem, especially if raw sludge is used.

There is an economic advantage in running the machine for the longest possible periods as the concentrator is suitable for prolonged operation without supervision. Suriyadasa (45) estimates running costs at about $18 per ton of dry solids in the raw sludge for operation 16 hours a day and 7 days a week. Berger and Warren (4) claim that both running and capital costs will come to this figure, and that vacuum filtration and drying beds are considerably more expensive. Although the latter costs may be presented in too favourable a light, there are many positive features of this process. The roto-plug concentrator is compact and flexible in operation. The equipment is slow-moving so wear and tear should be at a minimum, power requirements are low, and no conditioners are needed. A single machine deals with about 12 lb of solids an hour, so it should be suitable for small or medium sized works.

5. Other Methods

There are several other mechanical methods of dewatering sludge, two of which will be described briefly. The Permutit Company has developed a DCG (Dual Cell, Gravity) solids concentrator (37). The DCG concentrator is essentially a continuous-belt filter operating by gravity. Since no vacuum, pressure or conditioning agents are required, capital and operating costs are comparatively low. It consists of two separate cells formed by a cloth belt travelling slowly around two sets of guide wheels; the belt, a fine-mesh nylon screen, serves as a filter. Dewatering takes place in the first cell, cake formation in the second. As the cake grows to a certain size, the excess drops off at the end of the cell onto a conveyer belt for disposal. Cake moistures average 80 - 85% and the filtrate quality is high. The equipment costs for a small treatment plant would be much less than for a vacuum filtration unit, and in larger plants operating costs would be lower. This method is applicable to sludges that will form a coherent cake, so the feed concentration must be at least 2% TS.

The Heymann process (14) consists of a vibrating screen and squeeze rollers and is installed in several plants in Switzerland and Germany. The sludge is gravity-fed to the vibrating screens where it is moved slowly forward with the filtrate passing through the screens to a removal trough below. The sludge solids are then discharged by gravity to an endless belt screen which carries them under rollers for squeeze dewatering. The advantages of this process are that no chemical conditioners or other additives are needed, and the dewatered sludge is odourless. In large-scale installations there is a high solids content in the filtrate. The solution to this problem might be to thicken the filtrate by some means or dry it on sand beds, but this defeats the purpose of mechanical dewatering.

There are other mechanical dewatering processes in limited use in Europe and North America, including the Edco filter, or coil thickener, but most of these are in the experimental stage or of limited practical value. At the present time vacuum filtration, and to a lesser extent centrifuging, are the most widely accepted means of mechanically dewatering sewage sludge.

VIII HEAT DRYING AND INCINERATION

All the mechanical methods described above leave the problem of the final disposal of the sludge cake unanswered. Further drying from a moisture content of 50 - 80% or complete reduction of the sludge to a small-volume ash by incineration or some other means is desirable, and often essential. When there is no land available for surface distribution of liquid sludge and sanitary fills are exhausted, incineration is the only solution. Hot air drying will be discussed first, followed by incineration and two other techniques for reducing the sludge to an easily-disposable ash.

1. Hot Air Drying
2. Incineration
3. Wet Oxidation
4. Atomized Suspension

1. Hot Air Drying

When sludge must be dried to a moisture content of 35% or less for use in the manufacture of fertilizer or for final disposal, heat drying, although expensive, may provide the answer (5). Hot air drying is practiced in the USA mainly on fresh sludge.

The drying drum consists of a rotating drum in which drying occurs through injection of hot air or gas. The sludge is in continuous movement so that all particles are in constant contact with the hot air.

In the honeycomb drier sludge is supplied to an endless vertically-running honeycomb belt which runs through the drying chamber, the walls of which are provided with hot air jets.

Selective or oscillating driers are quick driers in which the sludge is dried to dust. At the end of the process a cyclone separates waste gas from the dry sludge.

The multistage drier consists of a series of superposed circular plates. Drained sludge is poured onto the top plate where it is swept into slits and falls onto the plate below and continues down the tower-shaped drier while hot gas is poured in a countercurrent on the sludge to be dried.

2. Incineration

Incineration frequently follows vacuum filtration or some other drying technique when disposal of large volumes of liquid or semi-liquid sludge is impractical. The ash resulting from incineration of sludge needs little space for disposal and as at Toronto (13) can often be used as innocuous fill. The economics of incineration depend on the moisture and BTU content of the sludge, the fuel value of the sludge varying approximately with the volatile content. Filter cake with a 60 - 70% moisture content can be burned with no, or very little, auxiliary fuel once combustion has started. Since incineration is expensive, such factors as the quantity and type of sludge, and the location of the treatment plant have an important bearing on the decision of installation. For large cities with huge quantities of sludge, incineration is essential unless the plant happens to border on the ocean where sludge may be carried out and dumped from barges. Flash drying of sludge in conjunction with refuse incineration should be economical as it provides final disposal and deodorization at a minimum initial and operational cost (34).

There are two main types of incinerators, the flash drier and the multiple-hearth furnace (1). In the flash drier sludge cake is mixed with dried sludge and is discharged into a vertical "hot tower", the material mixing with rising, superheated gases. The dried particles are removed and water vapour from the sludge passes off with the hot gases. The "dust" containing about 10% moisture may then be burned to aid heating of the gases used in the hot tower or used as a

fertilizer base. Leet (28) states that a typical activated sludge might contain up to 6% nitrogen and 5.5% phosphoric acid. Sludge in the form of a filter cake contains all the nitrogen and phosphoric acid, but its high moisture content, abnoxious handling qualities, and the presence of pathogenic bacteria render it of little or no market value. By flash drying the sludge may be reduced to a safe, stable, storable product that will have considerable agricultural value. The returns from the sale of heat-dried sludge help defray treatment plant costs.

In the multiple-hearth incinerator sludge cake is discharged onto the upper of a series of circular hearths located one above the other inside a furnace. Oil burners on the upper stages assist the heat rising from the lower hearths to dry the sludge. Mechanical rakes push the drying sludge from hearth to hearth, sufficient moisture being removed so that the sludge burns unaided on the lower hearths.

A novel type of incinerator known as the "Fluo-Solids" method has been in operation in the US (5, 29). Dewatered sludge is fed into a reactor which operates at high temperatures (1600°F) and low pressures (2-3 psi). Air and gases are passed upward through a horizontal plate and a layer of some inert solid material like sand so that the layer is suspended or "fluidized". Thermal decomposition of organic matter takes place rapidly under these conditions. Fuel is required only for heating and starting the reactor as long as the sludge is reasonably dry (about 65% water or less) and has a moderate organic content.

3. Wet Oxidation

In the conventional incineration methods described above, water must be evaporated from the sludge before the residues can be burned. In the wet oxidation (or Zimmermann) process, organic matter is oxidized to the same end products of ash and gases of combustion while dispersed in water (40). Sludge is preheated by waste gases and steam from the process,

then the sludge and compressed air are introduced in appropriate proportions into a reactor. Temperatures and pressures of 375°C and 2200 p.s.i. can be maintained in the reactor, but they are usually lower to suit the organic matter being oxidized. Only steam is needed to start the process. Flameless combustion occurs since the aqueous environment of wet oxidation holds the temperature down. After oxidation the contents of the reactor go to a gas-liquid separator. The reactor gases and steam may be superheated before expansion through a gas turbine and passage through the heat exchanger. The liquid phase, which contains the ash, goes to a humidifier where the air is heated and the oxidized liquid effleunt partially cooled before discharge from the plant.

The organic constituents of a waste are converted mainly to carbon dioxide and water, the inorganics are discharged in the liquid portion of the oxidized waste. Power costs are low since steam and electrical power may be obtained from the process. The operational power costs depend on this energy recovery which in turn depends on the solids concentration of the sludge and the volatile content. Under ideal conditions, when the sludge contains 4.5 - 5% solids, the process generates more power than it uses. The Zimmermann process is a closed system causing no odour or air pollution.

At Chicago's Southwest Works the liquid effluent from the reactor is piped to settling ponds where the residual ash (with high inorganic content, innocuous, and biologically stable) settles rapidly. The supernatant is similar to an anaerobic digester supernatant with high ammonia, volatile acids, and BOD content and should be returned to the sewage plant for full treatment.

There are now several wet oxidation plants in the USA. Guccione (19) in a description of the Chicago Plant estimates operational costs at about \$12 per ton of dry solids based on a 3% feed and 80% available capacity. The total costs amount to \$23 a ton. These costs will decrease if the sludge is thickened before oxidation. The capital costs are inversely proportional to the sludge feed concentration because

of the volumes involved. The Chicago plant has the capacity to oxidize 200 tons of dry solids per day, representing wastes from a population of two million people. The comparative cost of heat-dried sludge in Chicago is given as $38 a ton, considerably higher than the costs for wet oxidation.

4. Atomized Suspension

The atomized suspension technique permits the evaporation and drying of sludge followed by chemical treatment, if required, of the dried solids. Gauvin and Dlouhy (18) describe the process in general and its installation at Beaconsfield, Quebec.

Sludge is atomized at the top of a tower, the walls of which are kept at approximately 1400°F by hot gases circulating through the jacket. The small droplets decelerate quickly and become dispersed in the water vapour produced by their own evaporation. The suspension thus created flows down the tower. There is a large surface area available for heat and mass transfer so evaporation, followed by drying, is completed rapidly. At the end of the drying zone the suspension of dried particles can be subjected to a sequence of chemical reactions, for example, oxidation, reduction or nitration. Leaving the tower at the bottom are steam and by-product gases, and a solid residue. Close control over the system may be exercised by proper variation of the wall temperature.

The process features high reaction rates and high thermal efficiencies. By operating the reactor under pressure it is possible to recover the latent heat of vapourization in the form of steam. If the sludge has appreciable organic values it may be burned in the jacket surrounding the tower, eliminating additional fuel requirements. As in other dewatering methods, concentration of the sludge is desirable to minimize the volume of sludge to be processed, but primary, secondary or mixed sludges can be used. The process is thermally self-sufficient except for starting up, and either

electric or oil heating may be used for this purpose. Electric heating is simple and flexible, and although expensive, would serve small communities best. Power costs are lowest when highly concentrated sludge (20% solids) is processed.

The installation at Beaconsfield serves a population of about 14,000 and cost $35,000 initially. Low operating costs and a minimum of maintenance and supervision are claimed. There are no odours in the solids or gases and the condensate is clear.

IX COMPOSTING

The process of composting might be defined as biochemical degradation of organic materials to a sanitary, nuisance-free, humus-like material (8). Although composting is common in Europe and some other parts of the world, interest in North America has been limited. In 1965 there were only three municipal composting plants in the United States, although several pilot-scale plants had been established in the warmer parts of the country. There appears to be increasing interest in composting, however, with several new plants under construction or in operation. The problem in North America is one of handling and sorting the complex materials and finding markets for the compost. The quantity and character of refuse vary greatly from one area to another. Glass, ceramics, rags, plastics and non-ferrous materials must be picked out by manual labour (high costs) or grinding (leaving small, unwanted particles in the compost).

Most composting processes rely on the principle of aerobic oxidation of the organic matter (40). Organic material can be stacked into heaps which are turned for aeration and mixing at intervals until the compost has matured. Decomposition occurs in three weeks in ideal conditions, with an additional three weeks needed for curing in sheltered piles. Mechanical processes are becoming increasingly popular, where composting takes place in cells with forced or natural ventilation and continuous or frequent mixing. Composting takes five days in these units and an additional three weeks to mature.

The composting of sewage sludge with other organic materials may be achieved successfully in some cases, but there are several variables to be considered. The volume, moisture content and nature of the sludge, and the type and availability of the additives will determine whether composting is feasible. Plant nutrients and organic matter in the sludge make a compost more valuable. The location of the sewage treatment plants should not be far from the refuse collection

sites. Compostable materials must be separated from crude refuse. The refuse must be well-mixed and the moisture content adjusted to the optimum level for microbial decomposition. Aerobic oxidation can proceed with a moisture content of 30 - 100%, but the best range is 40 - 70% (40). This means that the sewage sludge should be well-concentrated, to about 55 - 60% moisture.

Finished compost should have a moisture content under 40% and should be suitable for agricultural disposal, or disposal on tips or waste ground. A good-quality compost is required if a reasonable price is to be expected from agricultural interests. The capital cost of a composting plant would be similar to an incineration plant of the same capacity, but land requirements would be greater and labour costs high if the refuse is sorted manually. Chambers (8) estimated that annual costs of composting in Canada might be $15 - 20 per ton. Where incineration is the only alternative, composting may be economically feasible.

SUMMARY

Various methods for the dewatering and disposal of sewage sludge have been reviewed. It is apparent that the economics of all these methods are governed to some extent by the volume of sludge to be processed, so the importance of thickening or concentrating the sludge cannot be over-emphasized. Thus the role of digesters and thickeners is a particularly significant one.

With regards to sludge disposal, Canada is fortunate in having a lengthy sea perimeter, many lakes and rivers, and a sparse population for the most part. Most communities can find ample space for lagoons, drying beds, sanitary fill sites, and land for disposal of liquid sludge. This is not so true of the more populous regions and the larger cities, however, where many of the difficulties found in parts of the USA and Europe are encountered. In these areas no one treatment or disposal method can be recommended.

The merits of the various dewatering and disposal techniques depend on the characteristics of the sludge, location of the treatment plant, population density, available land, and so on, and must therefore be evaluated in each individual case.

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